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Materials & Molecular Research Division

To be published as a Chapter in ENCYCLOPEDIA OF SCIENCE AND TECHNOLOGY, Ed. S.P. Parker, McGraw-Hill, New York

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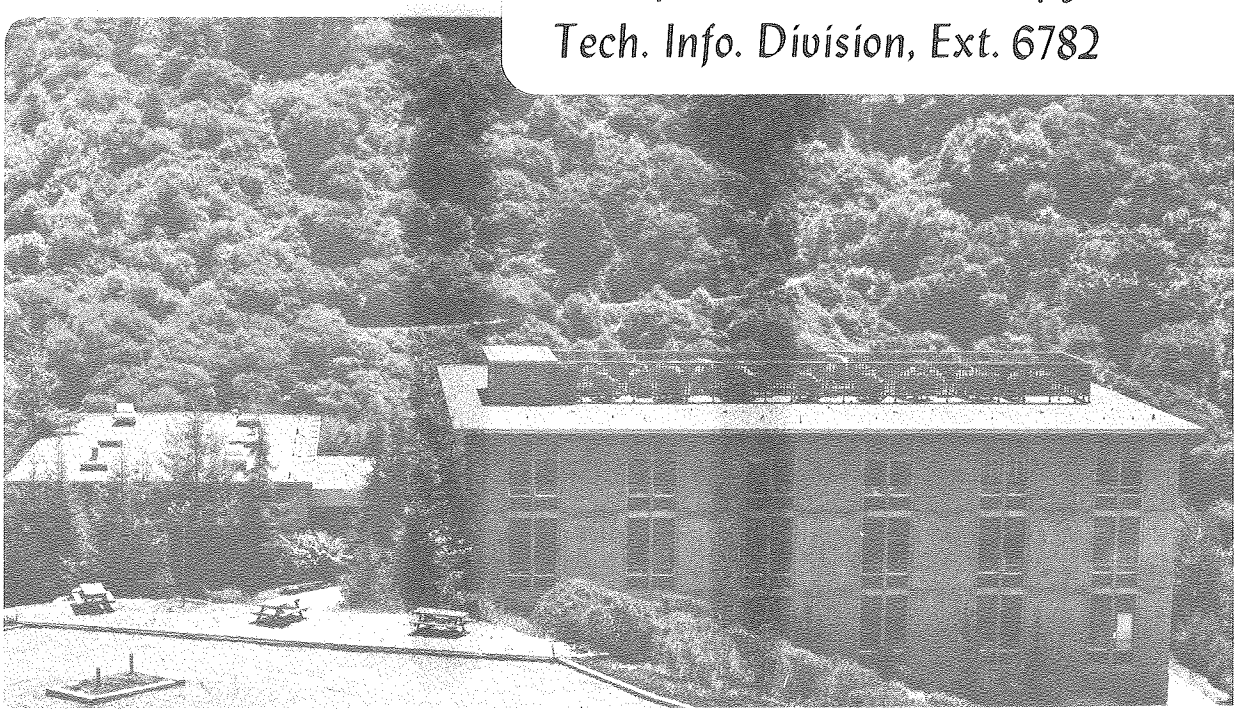
January 1981



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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LBL-12135

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This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

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SUPERCONDUCTING DEVICES

The unique properties of superconductors have led to the development of tiny measuring and computing devices that are superior in performance to their non-superconducting counterparts. Most of the devices operate at or below 4.2K, the temperature of liquid helium boiling under atmospheric pressure, and involve Josephson tunneling. The initial development of these devices took place in the second half of the 1960's; the 1970's have seen considerable growth of the field, including some commercial exploitation. Many areas of the field are currently changing very rapidly, and it is to be expected that there will be a high level of activity and a growing commercial market during the 1980's. In recent years, fabrication of the devices has increasingly involved photolithography and electron beam lithography, and superconducting junctions and circuits are now at the forefront of electronic ultra-miniaturization. This article briefly describes the four major areas of current interest: SQUID magnetometers, computers, standards, and detectors of high frequency electromagnetic radiation.

<u>SQUID Magnetometers</u> There are two types of Superconducting QUantum Interference Device for detecting changes in magnetic flux: The dc SQUID and the rf SQUID. The dc SQUID, so named because it operates with a dc bias current, consists of two Josephson junctions incorporated into a superconducting loop [Fig. 1(a)]. The maximum dc supercurrent, known as the critical current,

and the current-voltage (I-V) characteristic of the SQUID, shown in Fig. 1(b), oscillate as a function of the magnetic flux Φ threading the ring, with a period of one flux quantum, $\Phi_o = h/2e \approx 2.07 \times 10^{-15}$Wb. Thus, when the SQUID is biased with a constant current, the voltage is periodic in the flux [Fig. 1(c)]. The SQUID is almost invariably operated in the flux-locked loop shown in Fig. 1(d). A change in the applied flux gives rise to a corresponding current in the coil that produces an equal and opposite flux in the SQUID. The SQUID is thus the null detector in a feedback circuit, and the output voltage V_o is linearly proportional to the applied flux. Modern dc SQUIDs are fabricated from thin films, and usually involve Josephson tunnel junctions, resistively shunted to eliminate hysteresis in the I-V characteristics. For a number of years, the flux sensitivity remained at 10^{-5} to 10^{-4} Φ_o Hz$^{-\frac{1}{2}}$, but recently it has increased by several orders of magnitude, and is now approaching the limit set by the Uncertainty Principle. It appears that the dc SQUID is an ideal quantum-limited amplifier, although much work remains to be done to exploit this property fully.

The rf SQUID [Fig. 2(a)] consists of a single Josephson junction incorporated into a superconducting loop, and is so named because it operates with a rf bias. The SQUID is coupled to the inductor of an LC-resonant circuit excited at its resonant frequency, typically

30 MHz, although frequencies as high as 10 GHz have been used successfully. The rf voltage across the tank circuit vs. the rf current is shown in Fig. 2(b). When the amplitude of the rf current is properly adjusted, the amplitude of the rf voltage across the tank circuit oscillates as a function of applied flux [Fig. 2(c)], with a period Φ_o. The rf SQUID is also usually operated in a feedback mode, as indicated in Fig. 2(d). Most rf SQUIDs have been made from machined niobium components with a point contact junction. Although they have been used more widely than dc SQUIDs, their sensitivity is now considerably lower, and it seems unlikely that their performance will be able to match that of the dc SQUID.

Most SQUIDs are used in conjunction with input circuits. Figure 1(d) shows a voltmeter, the sensitivity of which is usually limited by Johnson noise in the resistor to typically 10^{-15}-10^{-12} $VHz^{-\frac{1}{2}}$. Figure 2(d) shows a magnetic field gradiometer, in which two balanced superconducting pick-up loops are connected in series with a superconducting coil coupled to the SQUID. If a uniform magnetic field is applied, no flux is linked to the SQUID, while the application of a field gradient $\partial H_z/\partial z$ induces a flux in the SQUID proportional to the difference of the flux in the two loops. Sensitivities of 10^{-13} Tm^{-1} $Hz^{-\frac{1}{2}}$ are typical. A gradiometer can be adapted to measure the paramagnetic susceptibility of tiny samples: One inserts the sample into one of the loops in the presence of a constant magnetic field, and measures the resulting change in flux. A system with a single pick-up loop is a magnetometer, with a typical sensitivity of 10^{-14} $THz^{-1/2}$; however, substantially higher sensitivites have been achieved.

SQUIDs have been widely used in low temperature research for well over a decade, but are now important tools for non-cryogenic applications. One example is the measurement of magnetic signals produced by the human heart and brain: A second order gradiometer ($\partial^2 H_z/\partial z^2$) (Fig. 3) gives sufficient rejection of external magnetic noise sources that the measurements do not require a shielded environment. SQUID magnetometers are of growing importance in geophysics, for example, in the measurement of rock susceptibility, and in magnetotellurics. A further potential application is as the transducer for gravitational wave antennas.

Computer Elements Typical high-speed digital computers, using large scale integration of semiconductor devices, have cycle times of 30 to 50 ns. The next milestone in the development is a cycle time of 1ns. To achieve this goal, both the device switching time and the time required to transmit a signal between different parts of the computer must be less than 1ns. Because the signal propagation speed is typically $10^8 ms^{-1}$, the second requirement implies that the largest dimension of the computer must be no greater than 0.1m. Although semiconducting devices with switching times substantially less than 1ns are certainly available, they dissipate considerable amounts of power. Because of the difficulty of extracting this power from a small volume, it does not appear feasible to reduce the physical size of a main-frame computer sufficiently to achieve a cycle time of 1ns. On the other hand, preliminary studies of Josephson junction computer elements made at IBM in the mid-1960's established that these devices had the combined requirements of very high switching speed and very low dissipation. A substantial research program has subsequently been maintained at IBM, and a few examples of their devices will be described here.

The circuits consist of many layers of metals and insulators, each one patterned by a photolithographic mask, and deposited over a superconducting groundplane on a silicon wafer. The linewidths are currently 2.5 or 5 μm. The Josephson tunnel junctions have hysteretic I-V characteristics, and are fabricated from lead alloys; their reliability is excellent.

The two essential components of a computer are logic circuits and memory cells. The logical operations necessary for a central processor involve two basic functions: OR and AND. One type of OR circuit involves a 2- or 3-junction interferometer or SQUID; the 3-junction version is shown schematically in Fig. 4(a), and as fabricated in Fig. 5(a). The interferometer is biased with a current below its initial critical current. A current pulse in either of the control lines, which in practice are films overlaying the interferometer, couples a magnetic flux into the device that lowers the critical current and induces a transition into the non-zero voltage state. An output from the gate thus represents A OR B. The fastest measured switching is 6 ps, while the propagation time along the transmission line is 7 ps, giving an overall gate time of 13 ps. Figure 4(b) shows an AND gate, which contains two junctions of different areas and hence different critical currents, asymmetrically arranged on the loop. Because of the asymmetries, simultaneous signals are required on the two inputs to induce a transition, producing an output voltage A AND B.

There are two types of cryogenic memory, a very fast cache memory that is coupled directly to the logic circuits, and a larger but slower main memory. One design for the cache memory [Fig. 4(c)] consists of an interferometer incorporated into a superconducting loop A "1", represented by a persistent supercurrent, or a "0", represented by zero supercurrent, can be written into the memory by the application of appropriate current pulses on the column line and the control lines. The contents of the cell can be read non-destructively by applying pulses to the column line and the sense line. The cell is designed for operation in an array, in which individual cells can be addressed; Fig. 5(b) is a photo-

photograph of an array with 64 cells used for testing purposes. The main memory loop is more compact, and consists of two-junction interferometers that are read destructively. Both types of memory dissipate power during writing or reading, but not during storage.

All of the necessary components for a computer have been constructed and successfully tested. Unless there is a major breakthrough in semiconductor technology or a new computer technology arises, it seems likely that the next generation of ultra-high speed computers will be based on the Josephson junction. However, such computers are unlikely to be available before 1990.

Standards The Josephson effects have an established role in standards laboratories. The most important applications are the measurement of the fundamental constant ratio e/h and maintaining the standard volt. When a Josephson junction is irradiated with microwaves of frequency f, constant-voltage steps are induced on the I-V characteristic at voltages $nhf/2e$, where n is an integer. Precise measurements of the voltages at which the steps are induced by a known frequency have led to the most accurate determination available of e/h. Furthermore, the standard volt at the National Bureau of Standards and at a number of overseas national laboratories is now maintained (but not defined) by these voltage steps, which may be compared periodically with the conventional standard cells. Since frequency can be measured very accurately, it is a relatively simple procedure for widely-spaced laboratories to compare their voltage standard.

Josephson devices have been used in two ways as noise thermometers for temperatures down to the milliKelvin range. In the first, a junction shunted with an external resistance is biased with a stable current. The Johnson noise voltage generated by the resistance, which is proportional to the absolute temperature T, induces fluctuations in the frequency of the Josephson radiation emitted by the junction. By measuring the bandwidth of these fluctuations, one can determine T. In the second method, a SQUID voltmeter [Fig. 1(d)] is used to measure the Johnson noise voltage generated by a resistor.

Other applications of SQUIDs include the comparisons of static voltages or currents to high precision, and the measurement of rf power levels. Josephson junction mixers can be used to synthesize frequencies up to 1 THz or more from microwave sources. Fixed point thermometers that rely on the reproducibility of the superconducting transition temperature of a series of metals are now available for the temperature range 0.015K (tungsten) to 7.2K (lead).

<u>Detectors of Microwave and Millimeter Radiation</u>

For over a decade there was extensive investigation of Josephson junctions, notably point contacts, as sensitive detectors of microwave and millimeter radiation. Various modes of operation were used including square law detectors, mixers, and parametric amplifiers. These devices met with varying degrees of success, but none was clearly superior to other non-superconducting devices. However, a new superconducting device that does not involve Josephson tunneling has recently been developed, the superconductor-insulator-superconductor (SIS) quasiparticle mixer. The device consists of a small-area tunnel junction, fabricated from Pb alloys, with the I-V characteristic shown in Fig. 6. The mixer is operated near the sharp onset in the current where the characteristics are highly non-linear. The non-linearity is used to mix the signal frequency, f_S, with the local oscillator frequency, f_{LO}, to produce an intermediate frequency $f_{IF} = |f_S - f_{LO}|$ that is coupled out of the junction into a low noise preamplifier. At 36 GHz, the detector has achieved the quantum limit, that is, it can detect single photons, and exhibits conversion gain. It is expected that photon-noise-limited performance can be extended to frequencies in excess of 100 GHz. Such receivers are likely to have a major impact on radio astronomy, and could be of great importance in such applications as space communications.

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Figure Captions

Fig. 1 (a) DC SQUID (the symbol ⨯ denotes a Josephson junction); (b) I-V characteristic with applied flux $\Phi = n\Phi_0$, $(n+\frac{1}{2})\Phi_0$; (c) V vs. Φ/Φ_0; (d) block diagram of dc SQUID in feedback loop with input circuit for measuring voltage (dashed line encloses cryogenic components).

Fig. 2 (a) RF SQUID coupled to LC-resonant circuit; (b) V_{rf} vs. I_{rf} with applied flux $\Phi = n\Phi_0$, $(n+\frac{1}{2})\Phi_0$; (c) V_{rf} vs. Φ/Φ_0; (d) block diagram of rf SQUID in feedback loop with input circuit for measuring magnetic field gradients (dashed line encloses cryogenic components).

Fig. 3 Second-derivative magnetic field gradiometer used for medical measurements. (Courtesy of S.H.E. Corp.)

Fig. 4 (a) Three-junction interferometer OR gate; (b) asymmetric two-junction interferometer AND gate; (c) high speed memory cell.

Fig. 5 (a) Three-junction interferometer OR gate; (b) 64-cell memory array.

Fig. 6 I-V characteristic of SIS quasiparticle junction.

ACKNOWLEDGEMENT

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Science Division, U.S. Department of Energy under contract No. W-7405-ENG-48.

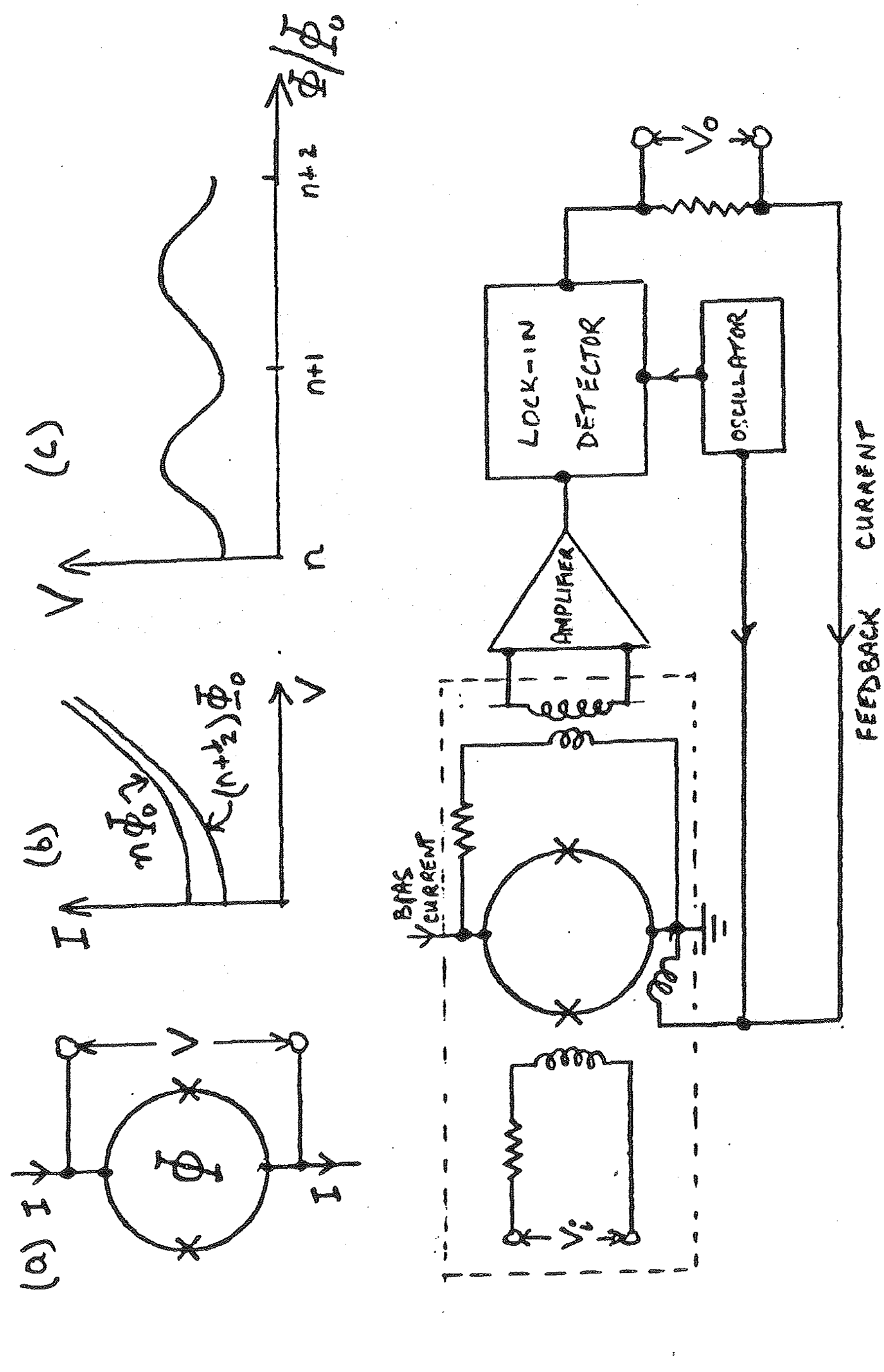

(a)
I
Φ
V
I
(b)
I
V
$n\Phi_0$
$(n+\frac{1}{2})\Phi_0$
(c)
V
n
n+1
n+2
Φ/Φ_0
BIAS CURRENT
AMPLIFIER
LOCK-IN DETECTOR
OSCILLATOR
FEEDBACK CURRENT
V_0
V_i

FIG. 1

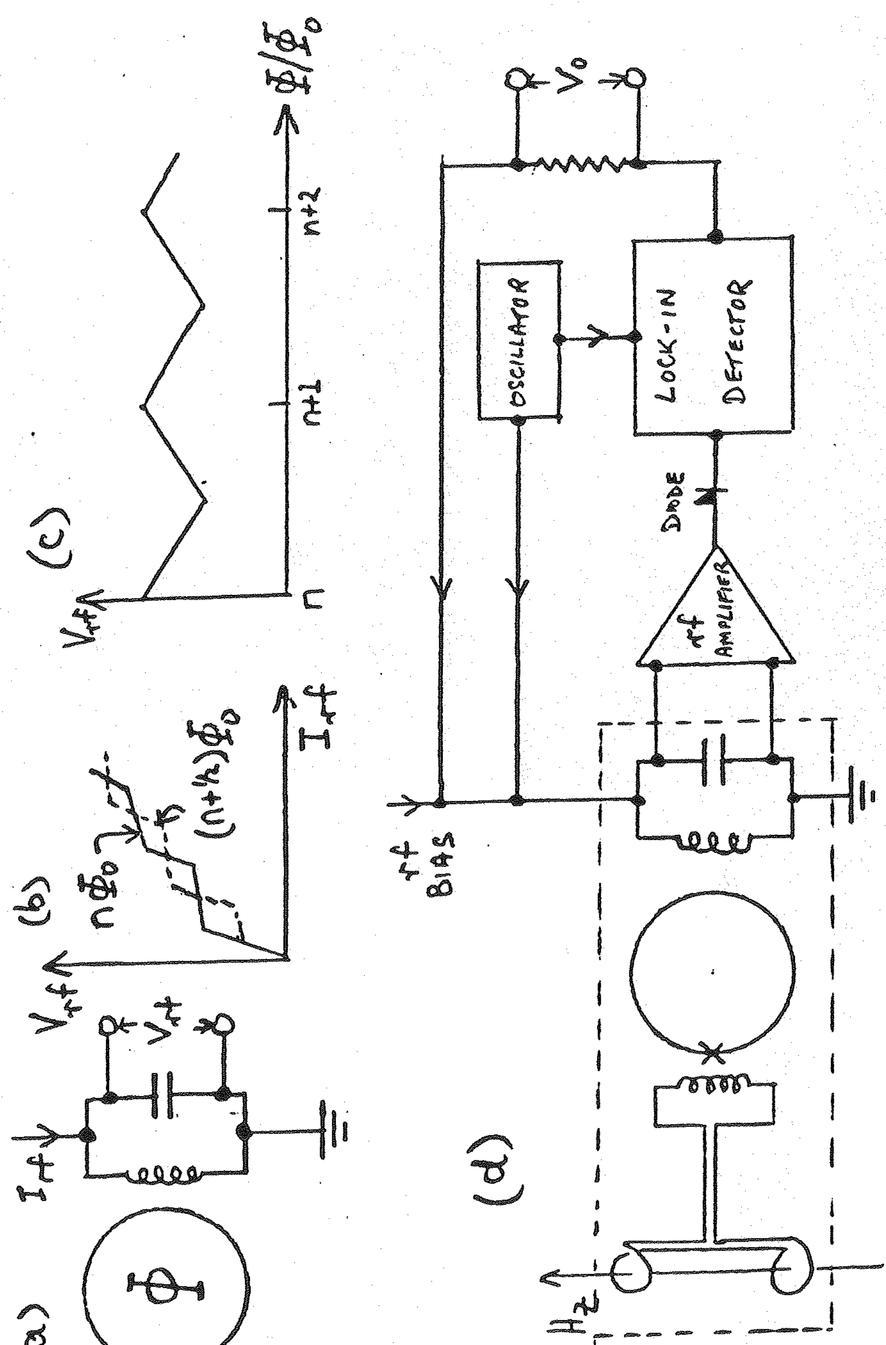

(a)
(b)
(c)
(d)
OSCILLATOR
LOCK-IN DETECTOR
DIODE
rf AMPLIFIER
rf BIAS
V_0
V_{rf}
I_{rf}
Φ/Φ_0
$n\Phi_0$
$(n+1/2)\Phi_0$
n
n+1
n+2
H_z

FIG. 2

Fig. 3

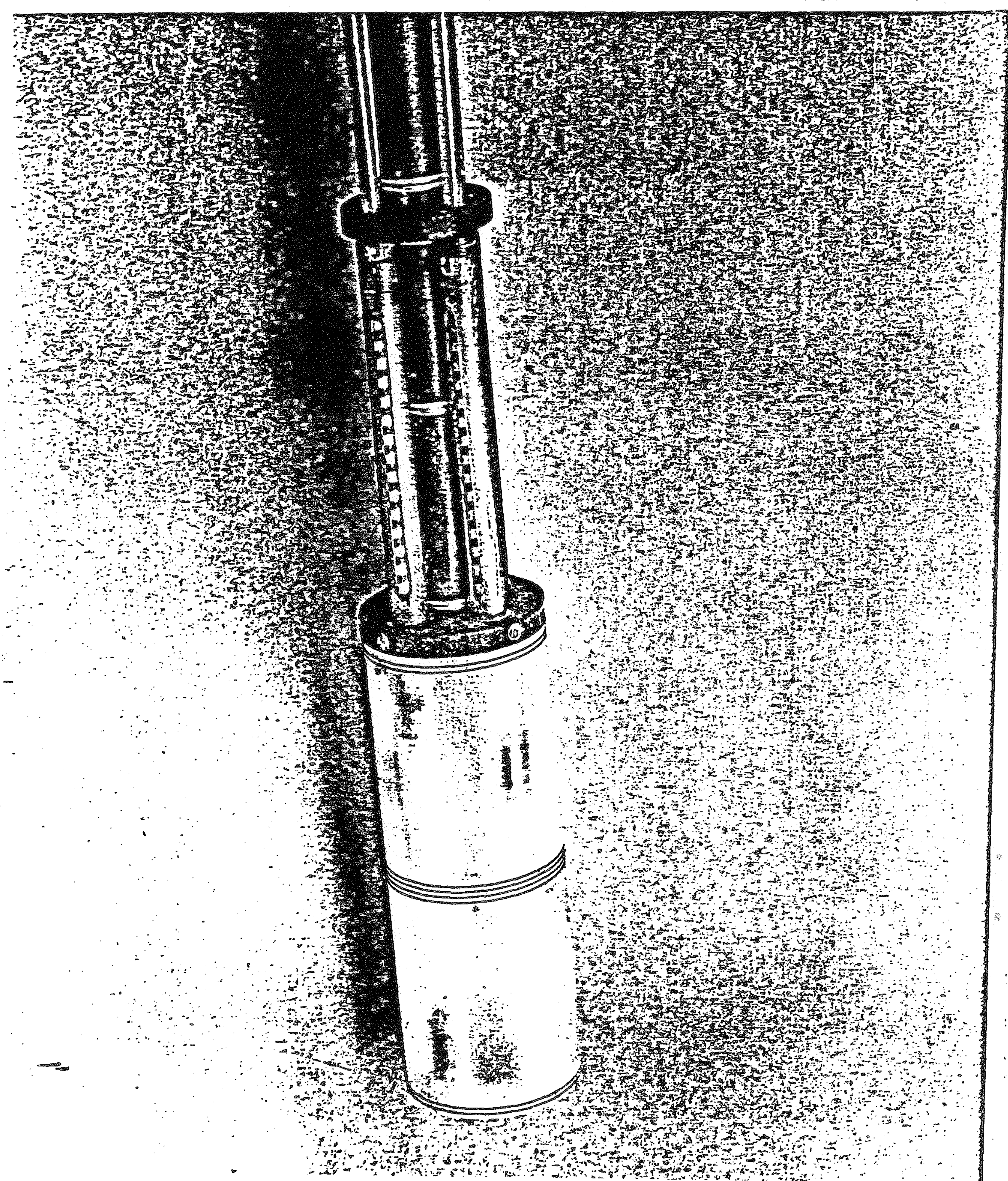


Fig 5(a)

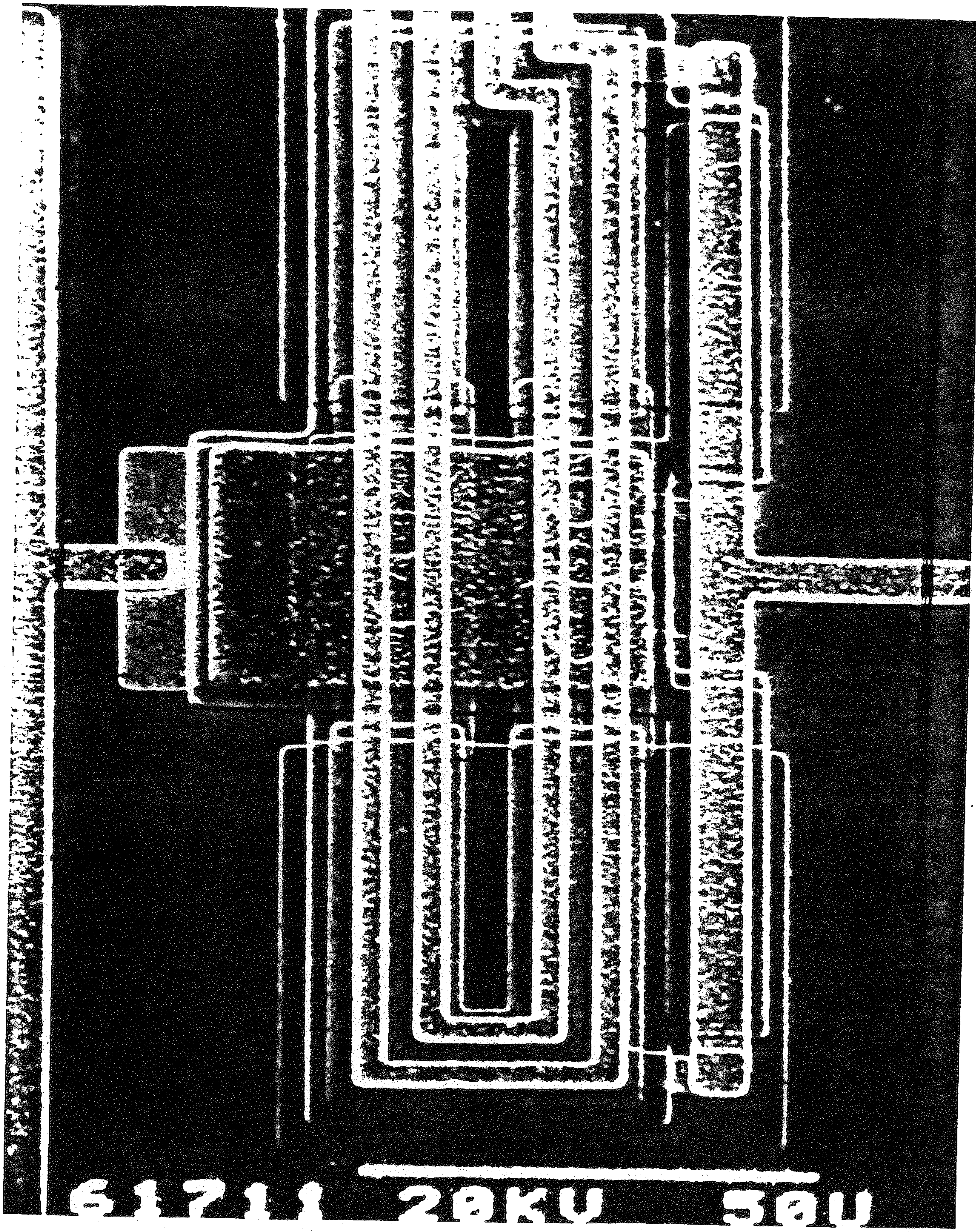
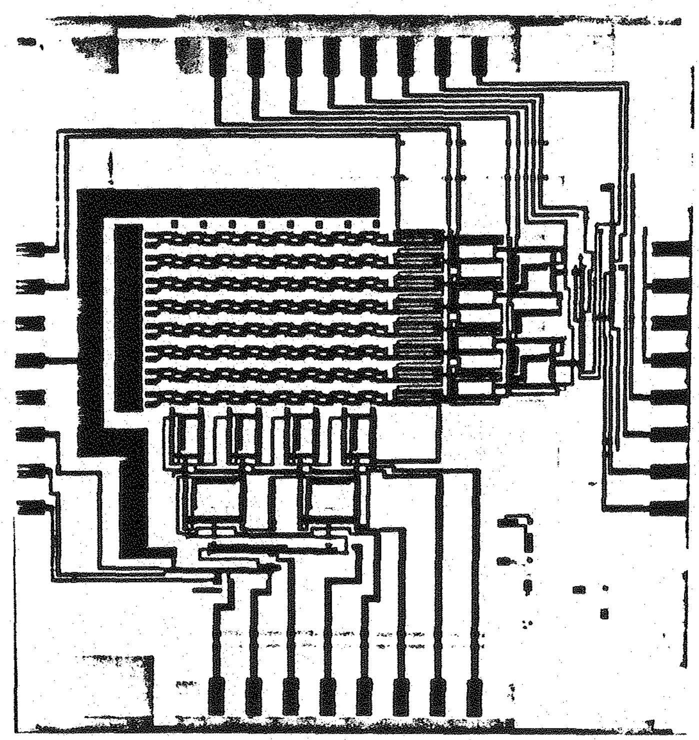


Fig. 5(b)



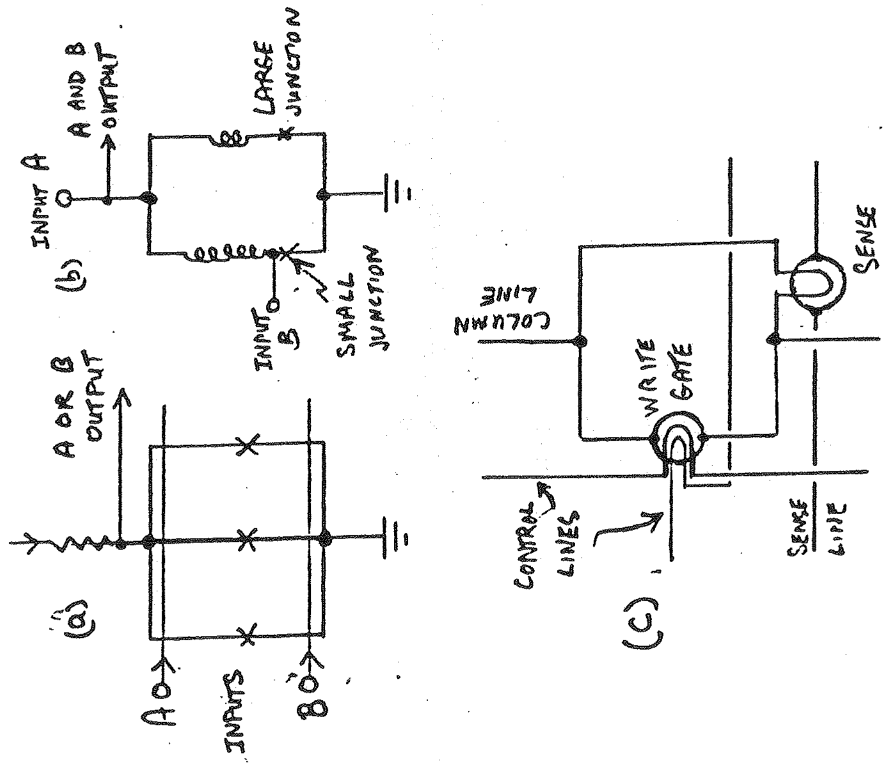

(a)
A OR B OUTPUT
A
INPUTS
B
(b)
INPUT A
A AND B OUTPUT
LARGE JUNCTION
INPUT B
SMALL JUNCTION
(c)
CONTROL LINES
WRITE GATE
COLUMN LINE
SENSE GATE
SENSE LINE

FIG. 4

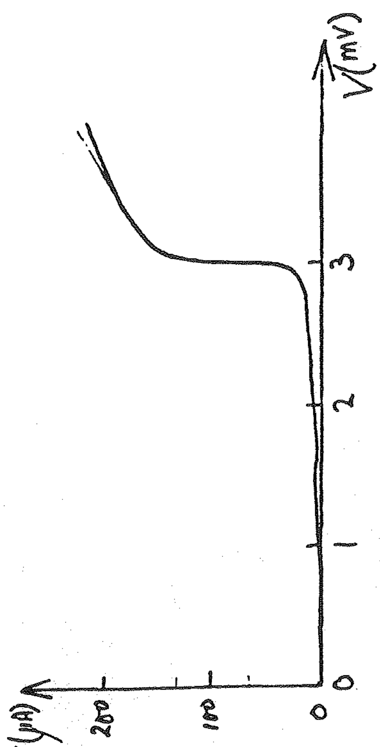


Fig. 6